VOL. 15, NO. 19, OCTOBER 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
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www.arpnjournals.com

ON THE ASSIMILATION OF GNSS PWV MEASUREMENTS IN HEAVY TO TORRENTIAL RAIN EVENTS IN DAVAO CITY, PHILIPPINES

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ABSTRACT

A standalone Global Navigation Satellite System (GNSS) receiver was utilized in this study to get a measure of the atmospheric water vapor in Davao City, Philippines. It aims to monitor the variability of GNSS precipitable water vapor (PWV) especially during heavy to torrential rain. The results of the study showed a positive correlation between GNSS-PWV and precipitation especially in these severe (heavy to torrential) rain events which implies that the assimilation of atmospheric water vapor measurements can improve forecasts of such events.

Keywords: GNSS-Precipitable water vapor (PWV), heavy to torrential rain, atmospheric water vapor.

INTRODUCTION

Precipitable water vapor (PWV) measurements derived from the datasets of a standalone Global Navigation Satellite System (GNSS) receiver was conducted in Davao City, Philippines for the years 2013 to 2016. The primary goal of the study is to monitor the variability of the GNSS-PWV estimates during heavy to torrential rain events. Several papers (Benevides *et al*, 2015; Wang *et al.*, 2015) have made case studies on precipitation and atmospheric water vapor and they have supported the existence of the positive correlation between GNSS-PWV and rain. These studies implied that a better analysis of the distribution of water vapor is a key factor to better understand the initiation of precipitation and provide more accurate forecasts of such events.

Davao region in the southern island of the Philippines has a relatively mild tropical climate with no real dry season. It is seldom affected by most of the typhoons that hit the country. However, it had been noted that flooding events have become a perennial problem. A study made on the management of climate change impact had noted that flooding is a recent but recurring phenomenon that the city needs to manage. Davao was also once touted as storm-free as it is located at 7°N of the equator, but the area was hit by the super typhoon Bopha in 2012. Indeed, there is a need to monitor the changing climatic conditions in the region.

The role of water vapor as a critical component of the greenhouse gases driving global weather and climate changes have been emphasized in many scientific reports. As such, the monitoring for any long-term changes in the amount of water vapor in the atmosphere is significant as it can help detect and predict changes in the earth's climate as well as improve weather forecasting. GNSS meteorology technique was used to investigate severe weather conditions in a campaign conducted (Realini et al., 2014) in western Java, Indonesia where results indicated a relation between the space-time inhomogeneity of GNSS-PWV and rainfall events in the tropics. The study made (Kanda et al., 2000) on the use of GNSS-PWV to monitor strong rainfall showed that periods of maximum GNSS-PWV tended to precede the onset of heavy rain, and that the precipitation frequency was higher for larger hourly increase in GNSS-PWV. The amount of precipitation occurring in an area can be thought of as due to the amount of water vapor present in the atmosphere, and the efficiency of various atmospheric mechanisms in converting the water vapor into precipitation. Atmospheric water vapor is a necessary condition for precipitation. A meaningful way to quantify the relationship between water vapor and precipitation can be made through analysis of seasonal variations and conditional probabilities of rainfall rate and total precipitable water.

EXPERIMENTAL SITE AND DATA SOURCES

The experiment was carried out in Davao City (7°4'N, 125°36'E), located in the eastern region of the southern Mindanao Island in the Philippines. The GNSS data files used in the study was from the receiver installed at the Ateneo de Davao University (ADDU) in Davao City, Philippines by the Space and Earth Geodetic Analysis Laboratory (SEGAL) of the University of Beira Interior - Portugal. Most of the meteorological data used were retrieved from the local station of the Manila Observatory (MO). The radiosonde data on the other hand was from the Davao Airport Station (Station ID# 98753), the lone operational upper atmosphere observation station in the southern part of the country. It is being operated and maintained by the country's weather bureau, the Philippine Atmospheric, Geophysical and Astronomical Services Administration or PAGASA.

DATA PROCESSING AND CALCULATIONS

The GNSS-PWV was calculated using the well-established method first proposed by the group of Bevis in 1992. The schematic diagram in Figure-1 shows the procedure in getting the PWV from the tropospheric delay solutions of GNSS signals. GNSS was originally created for surveying and geodesy applications but as the signal travels through the troposphere, the presence of water molecules introduce a delay in the signal propagation. Hence, the amount of signal delay is directly proportional to the amount of water molecules in the troposphere. Therefore, a careful observation of the delay in the signal can give a realistic estimate of the water vapor (Bevis *et al.*, 1992). This is the idea exploited in the use of GNSS in atmospheric water vapor estimation.

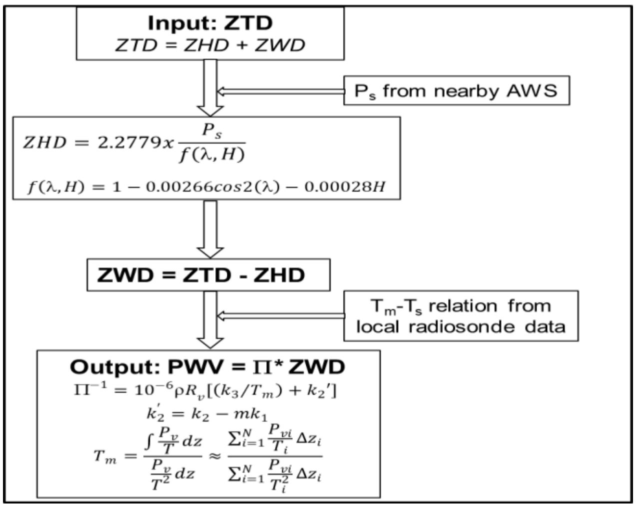

Figure-1. Schematic diagram of the procedure to derive GNSS-PWV from ZTD (Wang *et al.,* 2007).

The main meteorological product of ground based GNSS receiver is the estimate of PWV which is the vertically integrated quantity of atmospheric water vapor. In the technique proposed by (Bevis *et al*., 1992), the amount of PWV in the column of air above the GNSS station is retrieved from the delay of the signal propagation from each satellite to the receiver primarily because of the presence of the atmospheric water vapor along the slant path. The zenith total delay (ZTD) is used to estimate the delay in the vertical direction. It represents the tropospheric refraction in the zenith direction. Using ancillary measurements of surface pressure and temperature, GNSS-PWV is inferred from values of ZTD which are directly estimated from the GNSS data.

ZTD consists of two components: (1) the zenith hydrostatic delay (ZHD) which is due to the dry gases in the troposphere and the non-dipole component of water vapor refractivity and (2) the zenith wet delay (ZWD) which is due to the dipole component of water vapor refractivity in the atmosphere. The ZHD can be accurately inferred from precise measurements of surface atmospheric pressure or by using the Saastamonian model:

$$ZHD = 0.0022768P\ (1 + 0.00266\ [\cos 2\lambda + 0.0028H]) \quad (1)$$

In the given equation (Eq. 1) P is surface pressure in hPa, λ is the latitude of the GNSS station antenna in degrees, and H is the ellipsoidal height in kilometers. In most GNSS post-processing solution, it is the ZWD which gives the closest estimate of the atmospheric water vapor hence it had been suggested that it is best to obtain ZWD by subtracting ZHD from ZTD, or ZWD = ZTD - ZHD. Finally, the amount of precipitable water vapor retrieved from the wet delay can be expressed as (Bevis et al., 1992):

$$PWV = \Pi\ (ZWD) \quad (2)$$

The proportionality factor Π depends on the weighted mean temperature of the atmosphere, T_m, which can be computed based on radiosonde observation. Davis (Davis et al., 1985) defined and approximated T_m as:

$$T_m = \int \frac{\frac{P_v}{T}dz}{\frac{P_v}{T^2}dz} \approx \frac{\sum_{i=1}^{N}\frac{P_v}{T}\Delta z_i}{\sum_{i=1}^{N}\frac{P_v}{T^2}\Delta z_i} \quad (3)$$

where P_v is the partial pressure (in hPa) of water vapor, T is the atmospheric temperature (in Kelvin) and *i* is the *i*th pressure level. The calculation of T_m and GNSS-PWV would be exact if the vertical profiles of temperature and water vapor partial pressure were known exactly, obtained from radiosonde data. Since water vapor is mostly concentrated in the lower atmosphere, T_m is expected to be closely correlated to the surface temperature T_s. In order to achieve the best possible retrieval of PWV from an observed ZWD, the constant Π should be estimated using a value of the weighted mean temperature, T_m that is tuned to the specific area and season. This can be done by statistical analysis of a large number of radiosonde profiles. Bevis *et al*. (Bevis *et al*., 1994) derived a regression equation derived from radiosonde observation for over two years, under various conditions, taken from 27°N to 65°N from 13 stations in North America, from 0 to 1.6 km of altitude. Suparta and Iskandar (2013) also carried out a modeling of T_m over the West Pacific region for PWV estimation. Although the Bevis relationship has been widely used, several studies have also pointed out that the relationship between T_m and T_s is not constant. Instead, it depends on the local climate, season, and geographic and weather conditions (Bevis *et al*., 1992). This implies that an empirical T_m–T_s relationship based on local meteorological data will be more accurate for regional application.

Though most GNSS stations do not have collocated radiosonde station due to their sparse global distribution, Davao City has one of the few operating radiosonde stations in the country. A nearby weather station can also provide the surface temperature. Hence, it is imperative that since radiosonde data from the local station is available, a localized T_m–T_s relation should be computed for the PWV calculations.

Data from the morning and evening (00 and 12 UTC) radiosonde soundings for the whole year of 2015 were used to calculate for the T_m for each of the two daily launches. Average surface temperature during the period of the launch from the available Automatic Weather Station (AWS) was also computed. The regression equation given by equation (4) which is derived from using both the morning and evening sounding data sets was the T_m-T_s relation employed in the GNSS-PWV calculations. Both temperatures in equation 4 are measured in Kelvin.

$$T_m = 0.527T_s + 128 \quad (4)$$

RESULTS AND DISCUSSIONS

The annual GNSS-PWV variabilities are presented in Figures 2 and 3. The figures show the 2013 and 2016 time series plots of the hourly GNSS-PWV (blue). The hourly cumulative rain is also shown (red). The time series plots for the years 2014 and 2015 are not included because of the substantial amount of missing data for these years. No GNSS data were available for the months of May to August for 2014 and July to December for 2015.

GNSS-PWV is characterized by a clear annual cycle which is dependent on the local climate. Hourly GNSS-PWV ranges from 24.18 mm (lowest for 2013) and 21.34 mm (lowest for 2016) to as much as 72.54 mm (highest for 2013) and 72.01 (highest for 2016). Low PWV values are measured for the months of February, March and December while relatively high values are measured for the months of January, May and June, which also corresponds to the country's dry and wet seasons, respectively.

PWV is a factor for expressing the amount of water vapor in the atmosphere, and it can be used as an index for estimating potential rainfall. PAGASA had classified the rainfall events in the country in terms of the amount of cumulative rain on a per hour basis. Torrential means accumulated rain of 30 mm/h or more, intense is 25-30 mm/h, heavy is 7.5-15 mm/h, moderate is 2.5-7.5 mm/h and light is less than 2.5 mm/h. To characterize the behaviour of GNSS PWV in the presence of severe rain events, those classified as torrential, intense and heavy for the period of 2013-2016 were analysed. Initial analysis of moderate and light rains showed only very minimal variations in their PWV, hence they were no longer included.

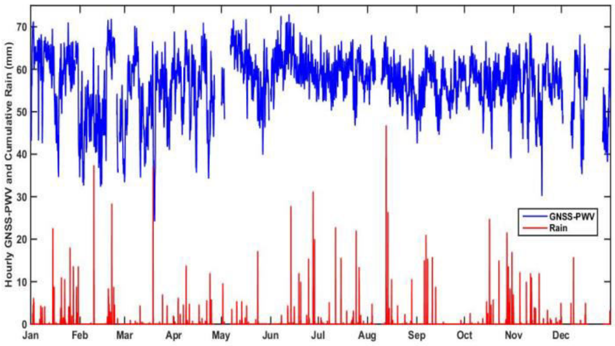

Figure-2. Hourly GNSS-PWV and Cumulative Rain for 2013.

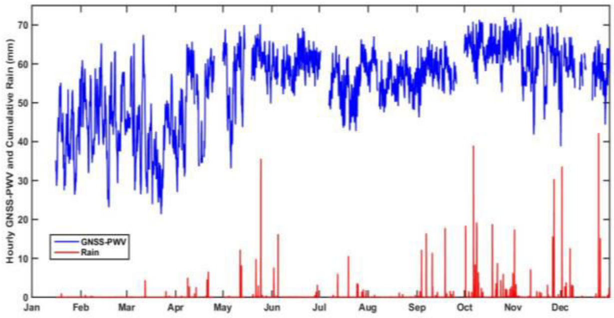

Figure-3. Hourly GNSS-PWV and Cumulative Rain for 2016.

Time series plots provided a better picture of the relation between the evolution of the GNSS-PWV and rainfall. While moderate rains follow small variations in GNSS-PWV, majority of the heavy to torrential rains are preceded by a gradual build-up of PWV. Figure 4 shows the torrential rain on February 9, 2013 with rain rate of almost 50 mm/h. The time-series plot shows that atmospheric water vapor as measured by the GNSS-PWV had been steadily increasing around 8 hours prior to the rain event with its maximum value approaching 70.0 mm. The actual torrential rain occurred a few hours later. Most of the heavy to torrential rain events analyzed in the study follow the said pattern; there is a significant rise in the GNSS-PWV before the rain and a decrease in its value subsequently after the rain and with the severe rain event occurring near the maximum GNSS-PWV value. In another torrential rain event shown in Figure 5 where four rain events with rainfall rates above 30 mm/h were observed over a span of three days, the characteristic build-up of the GNSS-PWV value prior to each rain event was observed. The significant reduction of GNSS-PWV was also noted after the rain event. In each of the rain events, it can be seen that the build-up phase of the GNSS-PWV takes longer than its reduction and there seem to be a time lag between the time the GNSS-PWV achieved its maximum value to the actual rain event.

The characteristic behaviour between the evolution of GNSS-PWV and rainfall is also observed during intense rains (rain rate of 15-30 mm/h) and even for heavy rain events (rain rate of 7.5 - 15 mm/h) as shown in figures 6 and 7. Similar to most of the torrential rains, there is a steady rise in the GNSS-PWV value prior to the rain event and it occurred near the maximum GNSS-PWV value with a significant reduction after the rain event. As noted in several studies (Kanda et al., 2000; Realini et al., 2014; Benevides et al., 2015), most severe rainfall events occur in descending trends after a long ascending period and that the most intense events occur after steep ascents in GNSS-PWV.

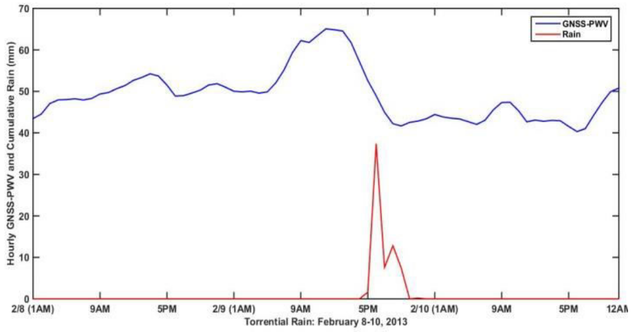

Figure-4. Torrential Rain - February 9, 2013.

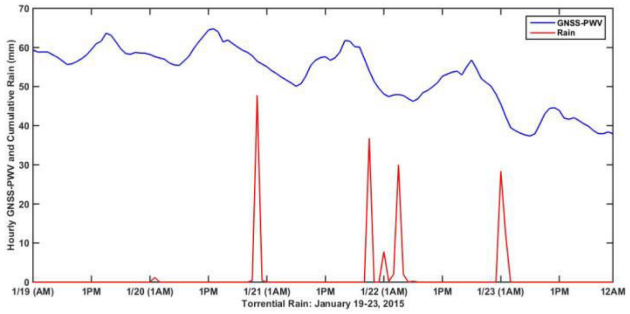

Figure-5. Torrential Rain - January 19-23, 2015.

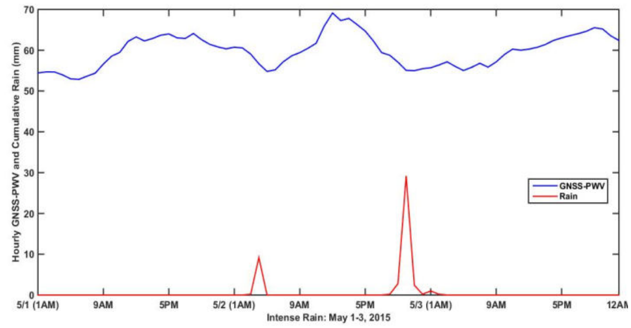

Figure-6. Intense Rain - May 2, 2015.

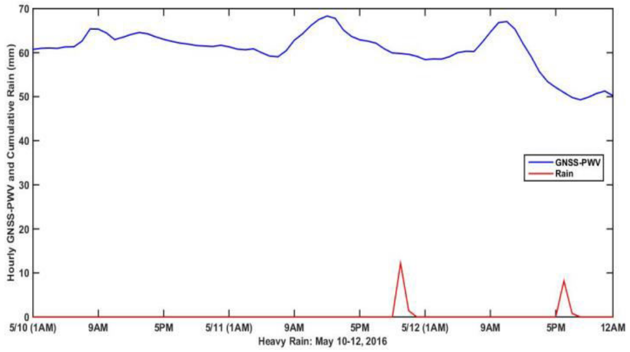

Figure-7. Heavy Rain – May 11-12, 2016.

To further characterize the time-varying GNSS-PWV in each of the rainfall events, the time-difference between the rain event and the time of the maximum GNSS-PWV was measured. The subsequent drop in the GNSS-PWV value after each rain was also determined. In all three rain classifications (torrential, intense and heavy), it was noted that most have time lags of 5-10 hours between the maximum GNSS-PWV and the actual rain event (Figure-8). This accounts for 88% of the said rain cases or 71 rain events out of the total of 81 rain cases analyzed. A GNSS-PWV drop between 5-15 mm was also observed in almost 80% of the three rain classes (Figure-9).

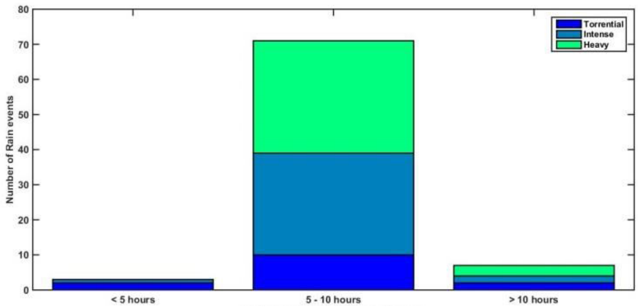

Figure-8. Time lag between Maximum GNSS-PWV and Rain event.

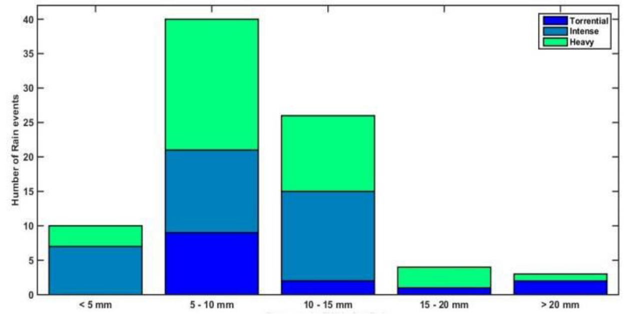

Figure-9. Decrease in GNSS-PWV after the rain.

Suparta *et al.* (2013) have noted that water vapor is an important parameter in short-range weather forecasting and that GNSS-PWV has a relationship with the measured rainfall. The distribution of water vapor and the development of precipitation systems mutually affect each other and the rapid rise in the GNSS PWV predicted the arrival of rainfall and is therefore useful in weather forecasts (Wang *et al.*, 2015). However, though the validity of observing GNSS PWV and its variation for monitoring heavy rainfall had been confirmed but GNSS PWV monitoring alone does not always provide sufficient information on the precursor of a severe storm.

CONCLUSIONS

In this study, the annual and seasonal variability of GNSS-PWV was measured for four-years (2013-2016) using a stand-alone GNSS receiver in Davao City, Philippines. In addition, its temporal evolution was also monitored during heavy to torrential rain events. Similar to the results of several studies, a gradual build-up of GNSS-PWV is observed prior to these rain events. A drop in GNSS-PWV was also noted thereafter. However, the maximum PWV value that precedes each rain event varies depending on the season and no cut-off value of PWV had been noted that predicts the occurrence of heavy to torrential rains.

The results of this study can provide the baseline data for atmospheric water vapor measurements in the area and the possible assimilation of GNSS-PWV in weather forecasting models in predicting rain intensity especially for severe ones (heavy to torrential rains). But it is recommended that the current methods in the data retrieval and GNSS-PWV calculations be further improved. Also, more in-depth analysis of the GNSS-PWV and rainfall relations should be made.

ACKNOWLEDGMENTS

The authors acknowledge the Commission on Higher Education (CHED) of the Philippine Government and De La Salle University Research Coordination Office (URCO) for the additional funds under the project number 47 F U 2TAY18-2TAY19 and the Center for Natural Science and Environmental Research (CENSER) of the De La Salle University for the administrative support to the project.

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